Microstructure Optics Design and Fabrication

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***Abstract*-Improved simulation techniques and nanotechnology fabrication facilities have been used to make high-performance metal mesh millimeter-wave through mid-infrared bandpass filters down to shorter wavelengths than previously possible. We report simulated and measured results for filters designed to support NASA flight instruments. The design, fabrication, and testing capabilities at our institutions are described. Continued progress in this area will result in a U.S. capability to produce essential optical components for astronomical instrumentation and other remote sensing applications.**

I. Introduction

Mid-infrared through microwave filters, beamsplitters, and polarizers are a crucial supporting technology for NASA's space astronomy, astrophysics, and earth science programs. The need for such devices is critical now, as space astronomy in particular continues to emphasize far infrared research programs in the new millennium [1]. Only in the past few years has the technology been available to design and fabricate with precision these microstructure filters: the new computer codes are able to do precise electromagnetic solutions to filter designs, while modern nanotechnology facilities can fabricate them. The current interest in nanoscience provides an opportunity for much improved filter production. We are applying new nanoscience fabrication techniques and improved equipment to make smaller and more precise structures that will result in higher-performance long-wavelength filters and enable construction of metal mesh filters for shorter wavelengths than previously possible.

In the far-infrared spectral region, where metal mesh structures are as large as several hundred micrometers, nanotechnology fabrication methods, accurate to small fractions of a micrometer, can produce nearly ideal structures that have higher in-band transmittance and better out-of-band blocking. In the mid-infrared range, this technology can produce components for use at wavelengths where conventional multilayer dielectric filters become unreliable and difficult to manufacture.

II. Filter Design

One of the most important and useful advances in the field is the availability of accurate numerical electromagnetic simulation codes [2], which have largely replaced analytic and equivalent-circuit approaches [3]. Although these codes were predominantly applied to microwave and radio devices, we have successfully extended their use to infrared frequencies of tens of terahertz. This software is capable of remarkably accurate simulations of the microwave through near-IR electromagnetic response of metal/dielectric structures and other frequency-selective surfaces. This finite-integral code divides the structure and surrounding space into many small elements, or grid cells. Maxwell's equations are formulated for each of the cell facets separately to produce a large set of matrix equations which are solved numerically. Although the software is capable of very accurate simulations, the calculations can take several hours of computer time for large or complex structures. But the approximate optical response of new structures can often be estimated in only a few minutes, allowing new ideas to be explored quickly. The most promising ones can then be optimized using the automated parameter sweep capabilities of this software.

Previous work indicates that our software tools are good enough to accurately predict filter performance, at least at normal incidence, saving a costly trial-and-error approach, although some of the predictions still await experimental confirmation. We use both commercial and academic software running on existing computers at our institutions to perform the design simulations. Careful study is needed to understand the small discrepancies that still remain between theory and experiment.

II. Filter Fabrication

NRL opened in October 2003 a new Nanoscience Research Laboratory which is now fully operational. The central core of the new building, a 5000 square foot class 100 cleanroom, has been outfitted with the newest tools to permit lithographic fabrication, measurement, and testing of devices. This includes deposition systems for metals and insulators, optical mask aligners, and etching systems. This is supported by chemistry stations and fume hoods for spinning on photoresists, baking, and developing the patterns that we use to produce the wavelength-scale metal and dielectric structures that comprise our optical components. Additional new equipment includes an electron beam writer for fabricating features down to 10 nanometers; a focused ion beam workstation for 10-nanometer-scale machining of materials; a scanning electron microscope for inspection of these small-scale devices, an optical pattern generator, several reactive ion etchers, and metal deposition systems.

Although infrared filters only require structures that are micrometer-sized or larger, nanometer-scale accuracy is needed to produce nearly ideal structures with straight edges and walls, and sharp corners that we can compare directly with numerical simulations. These high accuracy facilities will eliminate fabrication error as a source of disagreement between theory and measurement and will permit more exact investigation of any remaining discrepancies.

Equipment being used in this effort includes:

- Heidelberg laser pattern generator
- Suss MicroTec MA6 Mask Aligner with backside alignment (feature size ~ 0.2 micron)
- Temescal electron beam metal evaporator
- Axic Reactive Ion Etcher (RIE)
- Oxford Instruments ICP-RIE - Fluorine Deep Reactive Ion Etcher (DRIE)
- Leo Scanning Electron microscope (SEM)
- MRL Industries Low Pressure Chemical Vapor Deposition (LPCVD) System
- Oxford Instruments Plasma Enhanced Chemical Vapor Deposition (PECVD)
- N&K Spectrometer
- Olympus Optical Microscopes
- KLA-Tencor Alpha Step Profilometer

A. *Submillimeter Bandpass Filter*

We have perfected our lithographic techniques for depositing several different metals on various solid polymer substrates and developed a reliable and reproducible method for fusing the resulting individual filters together in a vacuum hot press in order to produce a multilayer solid polymer filter. Taking into account microwave transparency of various materials as well as our lithographic and fusing results, we settled on building filters by depositing copper on a substrate of low density polyethylene (LDPE). We have also explored various anti-reflection coatings that can be employed if desired and have demonstrated than they can be fused to the LDPE.

Fig. 1 shows a photograph of two 280 GHz bandpass filters constructed at Columbia University using this method, and a detail of their cross-shaped metal structures.

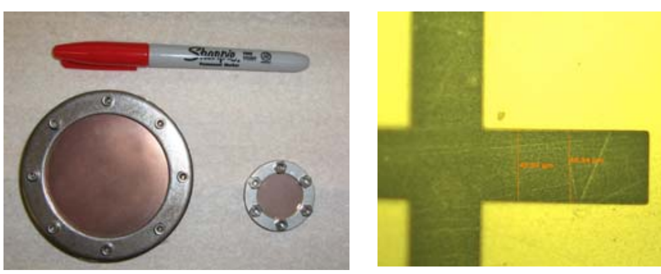

Fig. 1. Two completed three-layer solid polymer filters (3 inch and 1 inch diameter respectively). Photograph of Cu mesh structure; the cross width shown is 50 µm.

B. *Mid-infrared Bandpass Filter*

Freestanding, 3-µm thick Ni meshes were fabricated in the NJIT Microelectronics Research Center, using the electroforming process outlined in Fig. 2. Future samples will be coated with Au to decrease resistance losses and increase peak transmittance.

The resultant metal mesh, along with its calculated and measured transmittance spectra are shown in Fig. 3. This mesh was intended to have cross-shaped holes, but overexposure during the photolithographic process produced the octagonal holes shown in the photograph. Correcting the model to simulate the actual structure gives almost perfect agreement with measurement. The larger holes shift the peak to shorter wavelength and increase the peak transmittance without significantly altering the bandwidth. This is an area of current research and will be continued in this project. To our knowledge, this is the shortest-wavelength metal mesh filter ever produced.

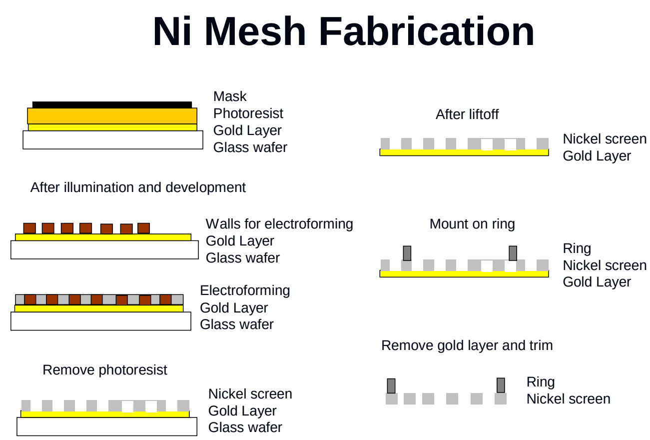

Fig. 2. The electroforming process used in freestanding Ni mesh fabrication.

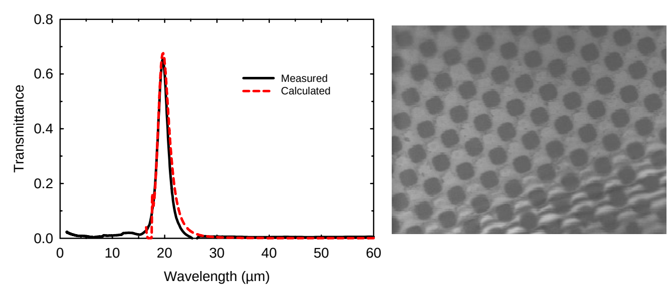

Fig. 3. Measured (solid) and calculated (dashed) transmittance spectra of the 20-µm bandpass filter. Photograph of the Ni mesh structure. The unit cell size is 17.3 µm.

C. *FORCAST Filter*

The SOFIA/FORCAST instrument requires a filter with a peak transmittance >90% at 38 µm and a bandwidth of 10%. The NRL nanomechanical resonator array [4, 5] is a very promising technology to adapt to infrared filter production. The freestanding silicon structure in Fig. 4, with periodicity of 2 µm, is approximately 20 times smaller than needed for the FORCAST filter, and demonstrates the high-accuracy fabrication techniques that are available to us. Compared with this structure, the larger sizes required for IR filters are relatively easy to fabricate. The freestanding structures eliminate reflection and absorption losses in substrate materials that have hampered previous attempts. Simulations indicate that when coated with an excellent electrical conductor, such as gold, this technology will produce a robust, high-performance filter that will meet the specifications for FORCAST.

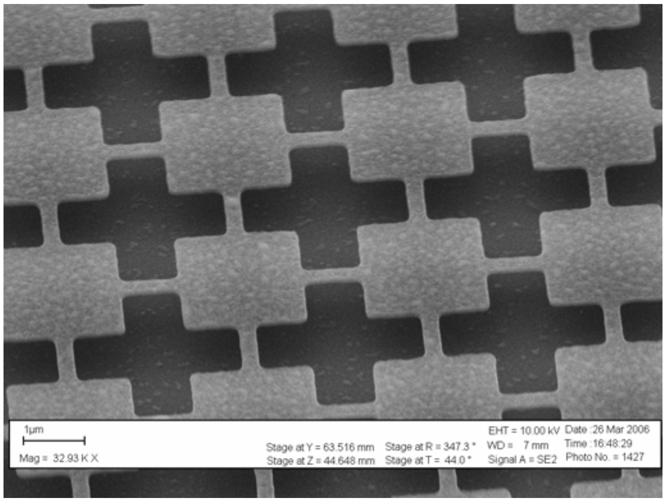

Fig. 4. The NRL nanomechanical resonator array. The unit cell size is 2 µm.

D. *Dichroic Beamsplitters*

The optical design for the SPIRIT Origin Probe requires a series of highpass filters with increasing cut-on wavelengths to be used as dichroic beamsplitters, which transmit short wavelengths to each detector and reflect long wavelengths to the next detector in turn. Figs. 5 and 6 show calculated spectra for possible multilayer metal mesh structures designed to meet the specifications for two of the dichroics. In the near future we will attempt to fabricate and test these beamsplitters. We will completely characterize the spectral and polarization properties of these beamsplitters at their specified 45º angle of incidence and cryogenic operating temperature.

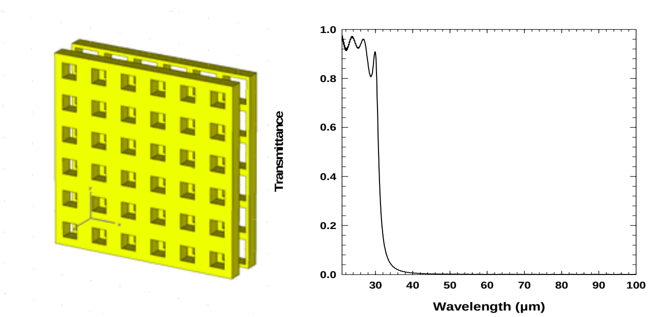

Fig. 5. A 30 µm highpass dichroic beamsplitter design and its predicted spectrum.

III. Optical Testing

The instruments at NRL and Columbia have combined continuous spectral coverage from microwaves to the ultraviolet, i.e., 25 GHz to 1.5 PHz, or 12 mm to 200 nm. Their spectral ranges overlap from 100 GHz to 1 THz (3 mm to 100 µm) which provides tests of measurement consistency accuracy.

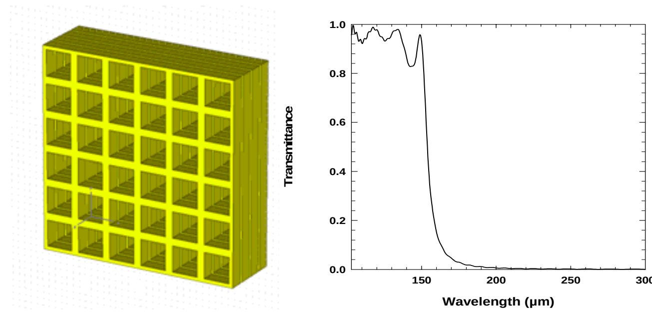

Fig. 6. A 150 µm highpass dichroic beamsplitter design and its predicted spectrum.

A. *Columbia Spectrometer*

We have constructed a wide beam-waist, polarization-sensitive Fourier Transform Spectrometer (FTS) with a bolometric detector system. It normally operates inside a Plexiglas box, which is over pressurized with dry N_2 to remove the water vapor spectral features. The box has been removed for the photograph in Fig 7. The FTS is a Martin-Puplett design based on a design developed at the University of Pennsylvania for other projects. The diameter of the useful beam of the FTS is ~12 cm, limited by the size of wire grids commercially available. The final optical element in the FTS is a converging parabolic mirror. Multiple sites along the converging beam exist in which the filter under test may be inserted. By allowing a single filter to be tested in many different parts of the beam (several different spot sizes on the filter), we can distinguish between problems localized to the inner or outer regions of the filter and those that appear over the entire surface. These measurements will enable us to understand and correct for non-idealities in the fabrication process as well as clarifying our understanding of the model and testing for reproducibility in our process at a manageable cost. The resolution is ~1 GHz. This high throughput device allows us to measure optical properties at frequencies as low as 80 GHz, a frequency inaccessible to most FTS systems. Measurements in this frequency range are important because it is near the frequency at which polarized cosmic foregrounds to the Cosmic Microwave Background (CMB) are at their minimum amplitude. By using a swept microwave source and the FTS cryostat, we can extend our range of measurable frequencies as low as 25 GHz, enabling measurements of optical elements over the entire frequency range useful for CMB science.

B. *NRL IR Spectroscopy Laboratory*

The optical performance of the metal meshes and assembled filters are also tested in a Bruker IFS 66v/S FTIR spectrometer (Fig. 8). This instrument, acquired in November, 2002, is a computer-controlled Michelson interferometer, which operates in vacuum to reduce atmospheric absorption and noise. Using several different sources, beamsplitters, and detectors, the spectrometer can measure transmittance and reflectance over the wavelength range from approximately 2 mm to 200 nm. The computer is also used for data reduction, analysis, and display.

Fig. 7. The Columbia Fourier transform spectrometer. Not shown are the Plexiglas optics enclosure and the 77 K (liquid nitrogen) and 300 K loads. During operation the optics enclosure is over-pressured with dry nitrogen to maintain a low-humidity environment.

Because many of the instruments for which we will be producing filters operate at cryogenic temperatures, the filters will need to be tested at these temperatures. A Janis Research Co. liquid helium optical cryostat has been designed to mount onto the vacuum box of the spectrometer with the optical tail extending down into the sample chamber. Liquid helium from a storage dewar passes through a heat exchanger inside the cryostat and into the cryostat sample chamber. By adjusting the current through a heating coil on the heat exchanger, the temperature of the sample can be held constant anywhere from room temperature to below 4 K. Inside the cryostat the entire sample and sample holder are surrounded by isothermal He vapor, so the temperature can be accurately measured by a Si diode sensor.

IV. Conclusion

The main goal of our research is to establish the routine capability to design and manufacture small quantities of filters and other IR components tailored to meet the exact specifications of future NASA missions. At the conclusion of this project we will have an extensive database of proven component designs and fabrication methods, and the expertise and facilities to manufacture filters and dichroics for NASA and the astrophysics community.

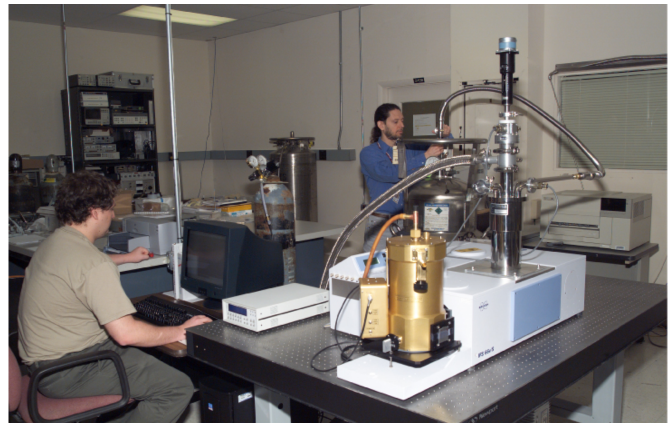

Fig. 8. The Bruker Fourier transform spectrometer (inside white vacuum box) and Janis optical cryostat (stainless steel cylinder mounted on vacuum box) that will be used for filter testing.

Acknowledgment

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